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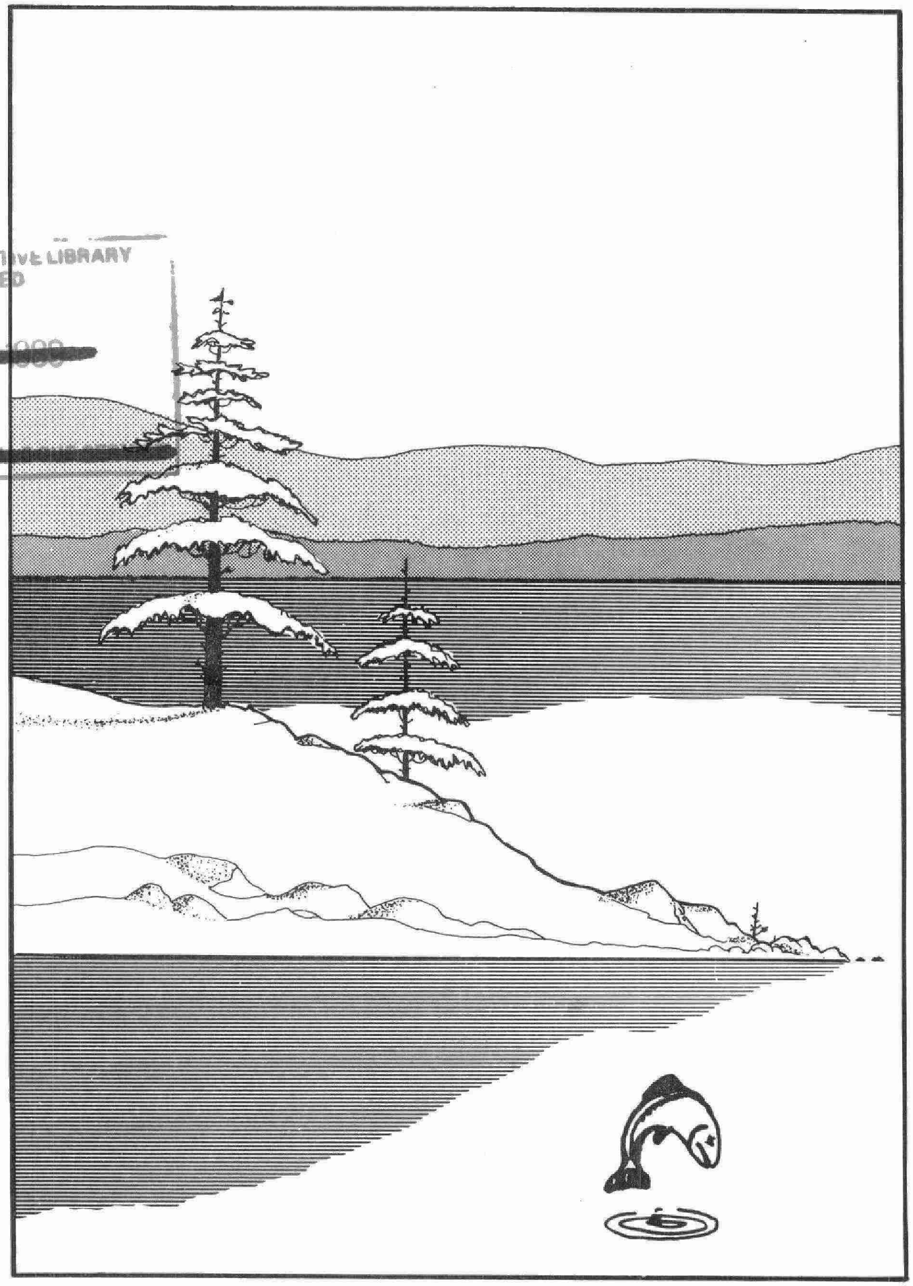
Lake Neutralization Experiments in Ontario 1981-1987

Summary of Phase 1



Ontario

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Lake Neutralization Experiments in Ontario 1981-1987

Summary of Phase 1

September 1988

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PREFACE

The Experimental Lake Neutralization program was jointly funded by the Ontario Ministries of Natural Resources and the Environment and was part of the Acid Precipitation in Ontario Study (APIOS). A Steering Committee comprised of representatives from the two Ministries was responsible for policy and administrative decisions. Scientific and technical advice was provided by a Technical Task Force of scientists of many disciplines from both Ministries. A group of international experts provided an external review of the program design. Coordination and management of the program was the responsibility of B.A.R. Environmental (formerly Booth Aquatic Research).

The use of trade names in this report does not imply endorsement of products or equipment by the Province of Ontario.

Copies of this report and the individual project reports and computer disks storing all the raw data from the projects are available from the APIOS Coordination Office at the following address:

APIOS Coordination Office
Ministry of the Environment
40 St. Clair Avenue West
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Toronto, Ontario
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ACKNOWLEDGMENTS

This report is a compilation of the work of many different groups and various other reports. Program design and data interpretation was a joint effort involving the Technical Task Force and the Steering Committee and BAR Environmental. We would like to acknowledge the work of the members of those groups. Many of the individual projects within the program were performed through the private sector. Portions of their data reports have been incorporated into this technical report. A listing of all participants in the program can be found in Appendix A.

Funding for the 1983/84 fisheries program was provided, in part, by the Canadian-Ontario Employment Development/New Employment Expansion and Development Program.

SUMMARY OF RESULTS

Bowland Lake

Whole-lake neutralization can reclaim acidified lakes if trace metals other than aluminum are low. The pH of Bowland Lake increased from 4.9 to 6.7 and the alkalinity increased from -0.3 mg/L to 4.5 mg/L. Total aluminum decreased gradually from 130 to 30 µg/L.

Neutralization successfully improved water quality in Bowland Lake for biota and provided a suitable environment for lake trout spawning and successful hatching of eggs. While lake trout growth rates were initially high after neutralization, they subsequently declined when 200 additional fish were added to the lake. This may have been related to competition for a limited food base.

Other organisms in the lake showed changes in species abundance and biomass but did not appear to be negatively affected.

(i) The phytoplankton community shifted from *Rhabdoderma*, a blue green algae, to a community dominated by several other species more representative of a non-acidic system.

(ii) Benthic algal abundance decreased after neutralization but eventually returned to pre-neutralization values. Species composition changed to reflect a community undergoing acidification stress in contrast to the original acidophilic community.

(iii) Changes due to neutralization in zoobenthos and zooplankton communities were primarily taxonomic, shifting to taxa more representative of non acidic conditions, e.g. a decreased abundance of the acidophilic rotifer *Keratella taurocephala*.

(iv) Quantitative changes in zoobenthos (reduced biomass and mean size of zoobenthos) and zooplankton (reduced crustacean plankton biomass

coinciding with increased rotifer and ciliate biomass, and increased abundance of Chaoborus punctipennis), appeared to be related to altered competitive and predatory interactions that may not be directly linked to lake neutralization.

Metal analysis of fish showed increased concentrations of mercury compared to pre-neutralization levels; however, concentrations remained low relative to human consumption guidelines and returned to pre-neutralization values the next year. Mercury increases are likely due to natural annual variations.

Between August 1983 and March 1986 the whole-lake pH, calcium and alkalinity of Bowland Lake decreased. About 40% of the added alkalinity was lost.

Trout Lake

In this low alkalinity lake, whole-lake neutralization successfully raised pH and alkalinity. The pH increased from 5.8 to 6.6 and alkalinity increased from 1 to 4 mg/L. Aluminum concentrations remained relatively unchanged at 30-35 ug/L.

While long-term studies are not yet complete, the short-term experiments showed that whole-lake neutralization provides additional protection against acidification, without adversely affecting the ecological community of the lake, including a lake trout fishery. It is premature to speculate on the long-term response of lake trout to neutralization since fish spawned after neutralization will not enter the fishery until 1988.

After neutralization there was a decrease in abundance of the rotifer Keratella taurocephala while the mysid population increased. Based on preliminary examination of the data major changes to the phytoplankton community were not evident.

Whole-lake pH, calcium and alkalinity of Trout Lake decreased between 1984 and 1986. About 25% of the alkalinity added was lost within 18 months.

SOMMAIRE DES RÉSULTATS

Lac Bowland

La neutralisation de l'ensemble du lac permet de restaurer un lac acidifié si la concentration de métaux à l'état de traces, aluminium non compris, est peu élevée. Le pH et l'alcalinité du lac Bowland sont passés de 4,9 à 6,7 et de -0,3 mg/L à 4,5 mg/L respectivement. L'aluminium total, pour sa part, est tombé graduellement de 130 à 30 µg/L.

La neutralisation a contribué à améliorer la qualité de l'eau pour le biote et à créer un milieu propice à la frai et à l'éclosion pour la truite de lac. Si la reproduction de cette espèce a connu une forte croissance après la neutralisation, elle a baissé quand on a eu ajouté 200 poissons supplémentaires. Ce phénomène est peut-être attribuable à la concurrence pour la nourriture, peu abondante.

Chez les autres organismes, des changements ont été observés quant au nombre et à la biomasse, sans effets négatifs apparents.

(i) Le phytoplancton, où dominait l'algue bleue Rhabdoderma, s'est transformé pour céder la place à plusieurs espèces plus représentatives d'un plan non acide.

(ii) Après la neutralisation, les algues benthiques étaient moins abondantes, mais elles sont revenues avec le temps à leur volume préalable. Leur composition s'est modifiée pour donner lieu à une communauté en proie au stress acide, alors que la communauté d'origine était acidiphile.

(iii) Les changements subis par le zoobenthos et le zooplancton par suite de la neutralisation étaient surtout d'ordre taxonomique, les communautés étant davantage représentatives d'un lac non acide. Par exemple, on dénombrait moins de Keratella taurocephala, rotifères acidiphiles.

(iv) Les changements quantitatifs observés chez le zoobenthos (réduction de la biomasse et de la taille moyenne) et chez le zooplancton (réduction de la biomasse des crustacés planctoniques du fait de l'augmentation de la biomasse des rotifères et des ciliés, et prolifération de Chaoborus punctipennis) ne semblaient pas liés à la neutralisation du lac comme telle, mais plutôt à la modification des interactions sur le double plan de la compétition et de la prédation.

L'analyse des poissons a révélé une concentration plus élevée de mercure après la neutralisation; la concentration était cependant faible par rapport aux recommandations pour la consommation et elle était revenue à son niveau antérieur l'année suivante. L'accroissement de la teneur en mercure est probablement dû aux variations annuelles.

Entre le mois d'août 1983 et le mois de mars 1986, le pH, la teneur en calcium et l'alcalinité du lac Bowland ont tous diminué. Concernant le dernier élément, le lac a perdu environ 40 % de l'alcalinité qu'il avait récupérée.

Lac Trout

La neutralisation de ce lac peu alcalin a permis d'augmenter le pH et l'alcalinité, l'un passant de 5,8 à 6,6 et l'autre, de 1 mg/L à 4 mg/L. La concentration d'aluminium est restée plus ou moins stationnaire, se situant aux alentours de 30 à 35 μg/L.

Quoique les études à long terme ne soient pas terminées, les expériences à court terme ont montré que la neutralisation de l'ensemble du lac contribuait à protéger celui-ci contre l'acidification, sans nuire pour autant à la communauté écologique du cours d'eau, dont la truite de lac. Il est encore trop tôt pour se prononcer sur la façon dont cette espèce réagira à la neutralisation à long terme, puisque les poissons fécondés après la neutralisation ne feront leur apparition qu'en 1988.

Après la neutralisation, on a assisté à une diminution du rotifère *Keratella taurocephala* et à une augmentation de la population de mysidacés. L'examen préliminaire des données semble indiquer que le phytoplancton n'aurait pas subi de grandes modifications.

Le pH, la teneur en calcium et l'alcalinité du lac Trout ont diminué entre 1984 et 1986. En l'espace de 18 mois, le cours d'eau a perdu environ 25 % de l'alcalinité qu'il avait reprise.

INTRODUCTION

In July, 1981, the Ministers of the Environment and Natural Resources announced a five-year investigation of the feasibility of using neutralization to protect Ontario lakes that are in danger of acidification, and to rehabilitate lakes already acidified.

The mandate of the program was to provide Ontario's natural resource managers with information regarding the feasibility of neutralization as a management technique while negotiations for abatement of acidic precipitation continued and control technology was developed. The study was in no way intended to divert effort or attention away from the necessity of emission abatement. Neutralization was and continues to be viewed as a temporary measure only. Neutralization alleviates the symptoms of the problem but does not eliminate the cause.

One of the initial objectives of this program was to test the feasibility of whole-lake liming to rehabilitate an acidified lake. Proof of successful rehabilitation would be the restoration of a healthy, self-sustaining sport fishery. Because of the importance of lake trout (*Salvelinus namaycush*) as a sport fish in Ontario and the sensitivity of lake trout to acidification, the study concentrated initially on rehabilitating a lake trout fishery. While the emphasis was primarily on the sport fishery, a viable ecosystem was required to support such a fishery. Therefore, many other biological, chemical and physical aspects of the ecosystem were monitored for their responses to lake neutralization.

The second objective of this program was to test the feasibility of whole-lake neutralization to protect an acid-sensitive lake. Success was judged by the ability to restore effective acid-neutralizing capacity to the lake without inducing negative biological effects.

A further objective was to evaluate site-specific neutralization (such as the addition of limestone to natural spawning shoals), as a cost-effective means of protecting the acid-sensitive developmental stages of lake

trout. This technique could be used in acid-sensitive lakes where whole-lake neutralization would be an expensive option, or to protect shallow, nearshore spawning areas of neutralized lakes if these were not adequately protected from spring-melt acid episodes by whole-lake treatments.

STUDY SITES

Physical and chemical characteristics of all lakes are given in Table 1; Fig. 1 shows the study area. The selected lakes all had low concentrations of metals related to smelter emissions such as copper and nickel so that the effect of neutralization on the biota could be addressed without introducing metal toxicity as an additional variable.

One acidic lake, Bowland Lake, and two lakes sensitive to acidification, Trout and Miskokway lakes, were selected for intensive studies.

Before neutralization, Bowland Lake had a self-sustaining yellow perch (*Perca flavescens*) population only. Although lake trout had been previously reported in Bowland lake, none were captured in 1983. Trout Lake has a complex fish community of 17 species, including lake trout and smallmouth bass (*Micropterus dolomieui*). The sport fish community in Miskokway Lake was similar to Trout Lake (Table 2).

A fourth lake (Fowke Lake) with a self-reproducing native lake trout population was chosen as a non-acidic control lake for bioassay experiments. A moderately acidic lake, Laundrie Lake, (directly downstream from Bowland Lake), was chosen for shoal liming experiments (site-specific neutralization). A mature lake trout population appeared to be spawning but no recruits had been captured in Laundrie Lake.

Field work began in the spring of 1982. Bowland Lake was neutralized in August, 1983, and Trout Lake was neutralized in May, 1984. Miskokway Lake was not neutralized and was eliminated from the study as a candidate lake for neutralization in 1984. Miskokway, however, was still tested for water chemistry and fish bioassays. Phase I,

the first five years of the study, was concluded in the fall of 1986 (Final Technical Report, 1987). A second phase of the study has since been initiated and will be completed in 1991.

TABLE 1: Physical and chemical characteristics of study lakes. Chemical data are presented as a range of values measured from June, 1982 to October, 1983 (August, 1983 for Bowland Lake). Some chemical characteristics for lakes that were not neutralized were measured in September 1986. Water samples were taken from the epilimnion, at mid-lake.

	Bowland Lake	Trout Lake	Miskokway Lake	Fowke Lake	Laundrie Lake
Surface Area (ha)	108.0	290.0	237.6	245	375
Maximum Depth (m)	28.0	37.8	42.0	53	20.4
Mean Depth (m)	7.0	11.0	14.8	14	4.9
Retention Time (years)	2.0	2.7	1.8		
pH	4.78-5.76	5.64-6.20	5.68-6.39	6.9-7.3	5.3-5.6
Alkalinity (mg/L)	-0.89-0.47	0.78-1.23	0.80-1.15	14.87-25.23	-0.93-+1.12
Total Aluminum (μg/L)	100-160	16-63	13-50	30-40	44-102
Conductivity (μS/cm)	35-42	28-29	24-27	50-55	23-35
Colour (true) (Hazen units)	1.5-7.4	7.0	16.6	9	13

FIGURE 1: Location of study lakes.

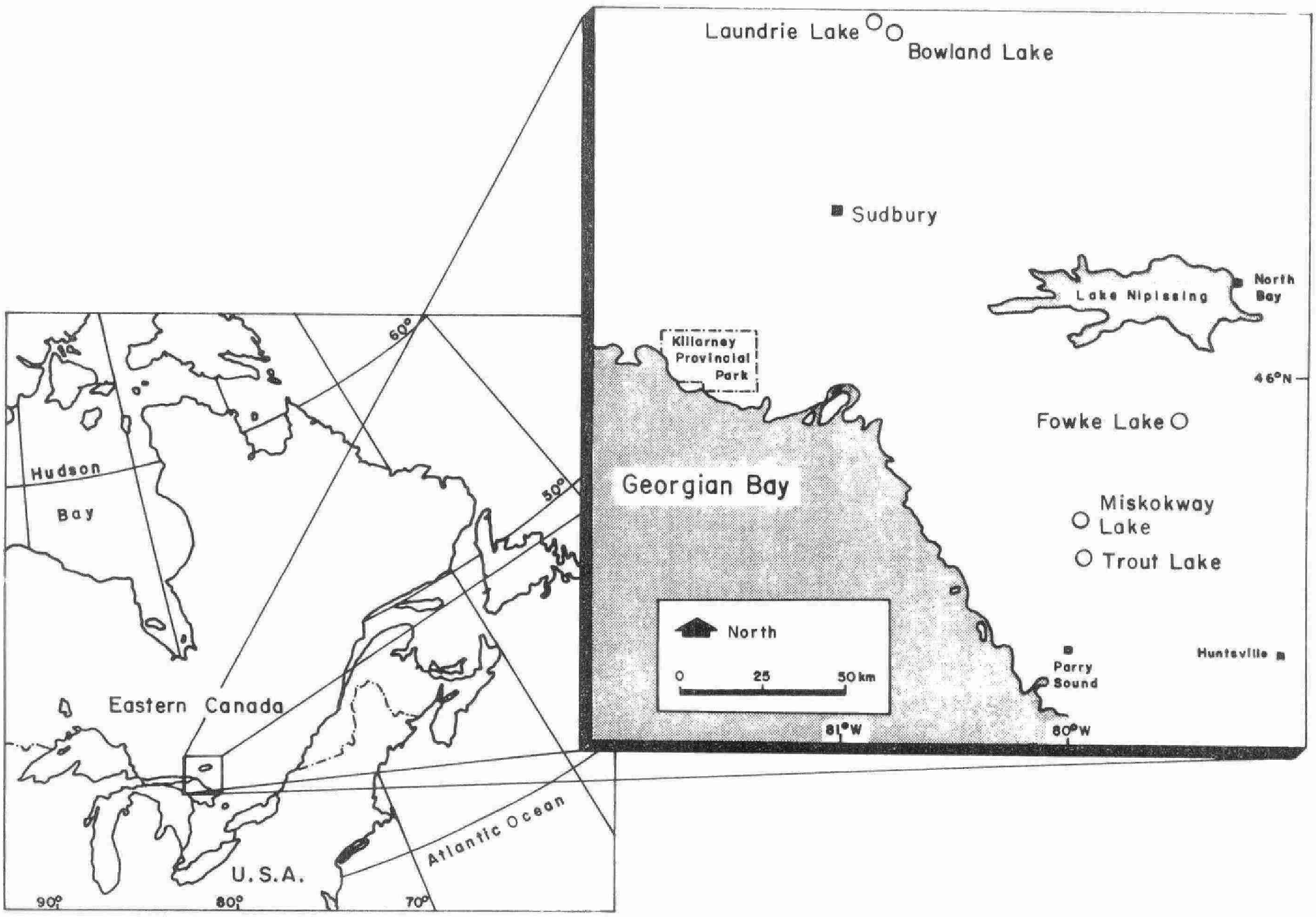


TABLE 2: Fish species collected in Trout Lake, 1982 to 1986.

Salvelinus namaycush	- Lake trout
Coregonus artedii	- Cisco
Umbra limi	- Central mudminnow
Catostomus commersoni	- White sucker
Phoxinus eos	- Northern red-belly dace
Notemigonus crysoleucas	- Golden shiner
Notropis cornutus	- Common shiner
Nortopis heterolepis	- Blacknose shiner
Pimephales notatus	- Bluntnose minnow
Semotilus atromaculatus	- Creek chub
Ictalurus nebulosus	- Brown bullhead
Culeae inconstans	- Brook stickleback
Lepomis gibbosus	- Pumpkinseed
Micropterus dolomieui	- Smallmouth bass
Perca flavescens	- Yellow perch
Etheostoma exile	- Iowa darter

METHODOLOGY

Neutralization Techniques

Calcite (limestone ($CaCO_3$)) was chosen because it is safe to handle, inexpensive and does not cause "pH shock". For Trout and Bowland lakes, delivery of calcite from nearby airports in Canso water bombers proved the most cost-effective.

A model developed in Sweden (Sverdrup, 1983) was used to calculate the amount of calcite required. This model accounts for lake pH, lake mean depth, particle size and dissolution efficiency of the neutralizing agent, and the base neutralizing capacity of the sediment.

Eighty-four tonnes of dry, powdered limestone (particle size - mean diameter 9.1 μm) were dropped in August, 1983 on Bowland Lake, from a Canso water bomber carrying a payload of approximately 2.4 tonnes. The lake was stratified during neutralization; however, since lake trout were not planted until after the fall turnover it was

not critical that the whole lake be neutralized immediately. Chemical sampling during and after neutralization showed that 47% of the limestone dissolved (Molot et al., 1986). This dissolution was lower than expected and may have resulted from electrostatic forces in the dry powder causing clumping of calcite particles which dissolved less efficiently.

In an effort to boost the dissolution efficiency of the Trout Lake application, a finer particle size (mean diameter 5.4 μm) of calcite (147 tonnes) was mixed in a 70% water slurry using a sodium polyacrylate dispersant (Busperse 39 from Buckman Laboratories). The slurry and dispersant enhanced dissolution efficiency (to 86%) without reducing the payload of calcite delivered by the Canso on each trip, making this technique more cost-effective than using dry powder. Trout Lake was neutralized in May, 1984 before the lake was fully stratified in order to maximize the volume of lake which received calcite (Molot et al., 1986).

Shoal liming on Laundrie Lake was done with three grades of calcite: 1/8", 3/4", and a mixture of these two plus 6" rock. Several replicates of each treatment were placed in 1 m^2 plots at five sites to test the survival of lake trout eggs in artificial incubators. Water chemistry was measured from within the incubators on alternate days during spring-melt.

At Miskokway Lake, one half of a shoal which was known to be used by spawning lake trout, was neutralized to test whether lake trout would avoid the light coloured calcite. Baskets were buried randomly in both neutralized and unneutralized sections to assess the distribution of naturally spawned eggs.

Water Chemistry

In Bowland and Trout lakes, water samples were collected monthly before and after neutralization (ice-conditions permitting). Water samples from the deepest mid-lake basin were volume-weighted to provide an estimate of whole-lake

conditions and concentration depth profiles were sampled for some parameters. pH, alkalinity, calcium and aluminum were measured, in addition to nutrients, other cations and anions and trace metals.

In Bowland Lake extensive chemical sampling was conducted over the period of addition of calcite to describe the immediate chemical responses of an acidic lake to neutralization.

An intensive three-to-eight-week program was implemented in Bowland and Trout lakes during March and April, the period of spring melt, in 1983, 1984 and 1985 to sample the quality of nearshore water. Transects running perpendicular to shore were sampled at 0, 1 and 2 m below the bottom of the ice. Additional sites located over possible lake trout spawning shoals were sampled at the surface, on the bottom and interstitially in the shoal rubble. The purpose of this sampling program was to determine whether whole-lake neutralization mitigated nearshore episodes of increased acidity and high aluminum.

Biological Sampling Programs

Bowland Lake:

Surveys in Bowland Lake documented the status of the planktonic, macrophyte and benthic invertebrate communities, pre- and post-neutralization. Benthic algal communities were mapped and described during shoreline cruises made in the late summer from 1982 to 1986. A littoral zone survey assessed macrophyte distribution before neutralization in the summer of 1982 and again in 1985 after the lake was neutralized. The benthic invertebrate community in Bowland Lake was surveyed in 1982, 1984 and 1985. Diver searches, bottom sampling with dredges and cores, and colonization rates for artificial substrates were used to provide a quantitative assessment of the benthic community.

Phytoplankton and zooplankton were collected monthly at the mid-lake station using a 3 L closing water bottle and a Schindler-Patalas trap respectively. Portions of samples from discrete depths were pooled to give a single volume-weighted sample.

Following neutralization, fingerling, yearling and two-year-old hatchery lake trout and adult lake trout from other lakes were stocked in Bowland Lake in late fall 1983 and again in 1985. The fish community in Bowland Lake was initially assessed in late summer and fall of 1982 and there was a detailed assessment throughout the open water period in 1983. From 1984 to 1987 the community was assessed in the spring and fall. A variety of standard gear was used (e.g. emergent lake trout traps, gill nets, minnow traps and trapnets). A representative sample of yearling yellow perch was tested each year for mercury concentration.

Bioassays of sensitive stages of lake trout were used to simulate responses that might be occurring in nature. Each fall, hatchery lake trout eggs were transported to the study lakes and the circumneutral reference lake (Fowke Lake) and placed in incubators at 1 m depths on shoals around the lakes. These eggs were allowed to develop through the winter until after ice-out in the spring. Periodic sub-sampling provided estimates of mortality at various stages of development and hence the time of year at which any eggs and fry were dying.

A second bioassay experiment exposed juvenile hatchery-reared lake trout in cages to worst-case water conditions immediately under the ice during spring-melt and again shortly after ice-out. Mortality rates were used as an index of toxicity of nearshore water quality before and after neutralization.

Trout Lake:

Phytoplankton and zooplankton were collected monthly as at Bowland Lake. Fish communities were assessed each spring with standard netting gear as at Bowland Lake and in the fall with additional effort using electrofishing boats for the collection of spawning lake trout.

There were lake trout egg bioassays each winter in conjunction with the bioassays on Bowland and Fowke lakes. Caged lake trout fry were exposed under the ice each spring.

RESULTS AND DISCUSSION

Water Chemistry

Whole-lake Chemistry

Major chemical changes occurred in Bowland Lake after neutralization. The pH increased from 4.9 to 6.7 and the alkalinity increased from -0.3 mg/L to 4.5 mg/L as calcium carbonate. Total aluminum levels decreased gradually from 130 to 30 µg/L and manganese showed a similar trend (Fig. 2). The lake became less transparent and Secchi depth decreased from 6.6 m in 1983 to 5.4 m in 1984.

After the addition of limestone slurry to Trout Lake, the pH increased from 5.8 to 6.6 and the alkalinity increased fourfold from 1 to 4 mg/L as calcium carbonate (Fig. 3). The concentrations of aluminum and manganese were initially low in Trout Lake and levels remained relatively unchanged after neutralization (aluminum ranged from 30-35 µg/L and manganese from 26-28 µg/L).

Reacidification

The reacidification rate of treated lakes must also be considered. The continuing input of acidic water will cause the lake to return to its previous, acidified state. While acidification may have originally been a slow process, reacidification may occur at a much faster rate as the buffering capacity of the watershed has already been depleted. Models are available to predict the rate of pH change within a neutralized lake. The models however, have not been calibrated for Canadian climate and geology.

After neutralization, Bowland Lake began to reacidify at a rate that was similar, although not identical, to the lake reacidification model proposed by Sverdrup (1984) (Fig. 4). Between August 1983 and March 1986 about 40% of the added alkalinity was lost. Spring-melt pH depressions seen on Bowland Lake were more severe than those predicted by the theoretical model, which was developed for the Swedish climate. Similar chemical changes were seen in Trout Lake after neutralization but the magnitude of change

FIGURE 2: Bowland Lake: Volume weighted whole-lake pH, alkalinity (Alk), calcium (Ca), total aluminum (Al), and manganese (Mn) concentrations from 1982 to 1985.

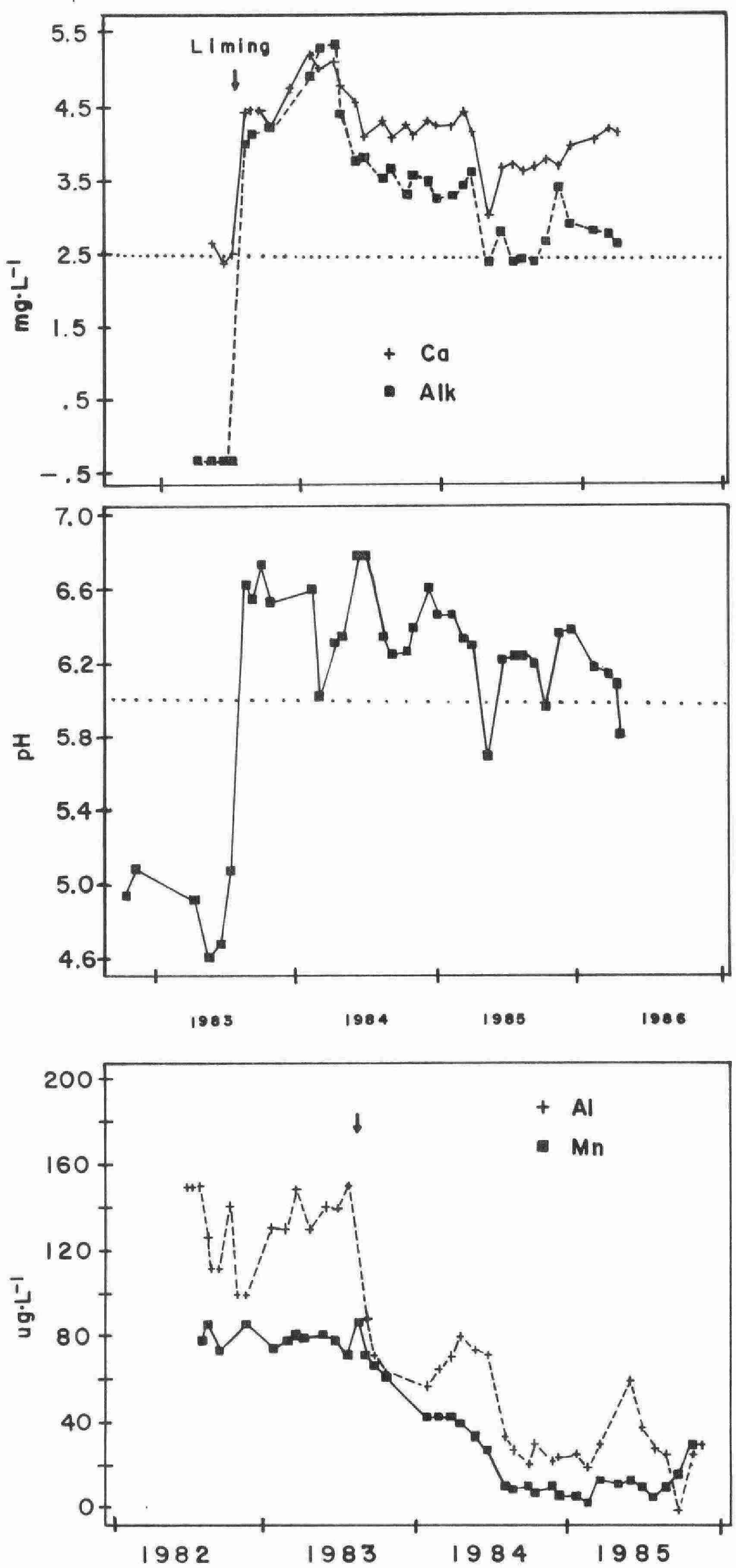


FIGURE 3: Trout and Miskokway Lakes: Volume weighted whole-lake alkalinity, calcium and pH from 1982 to 1985.

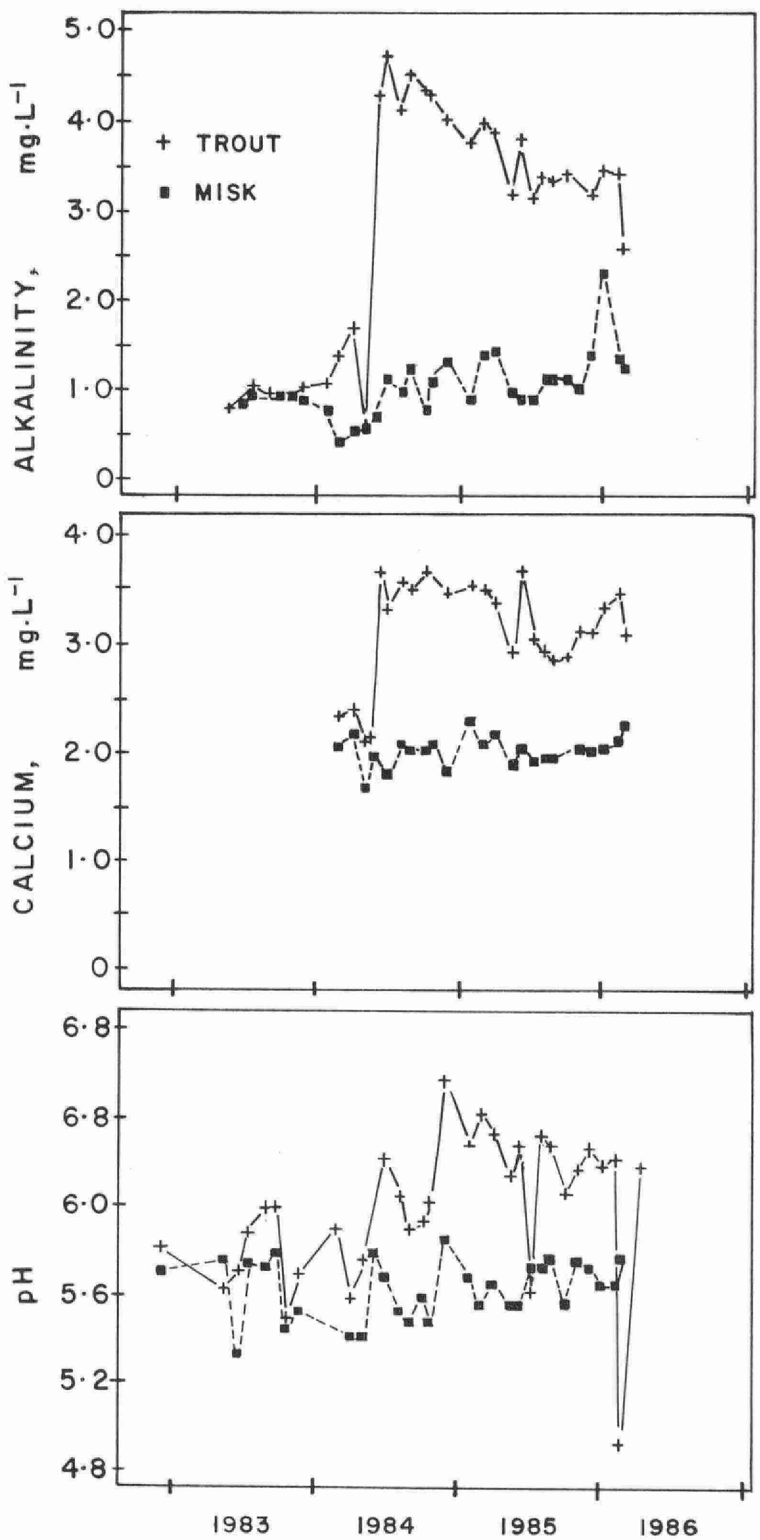
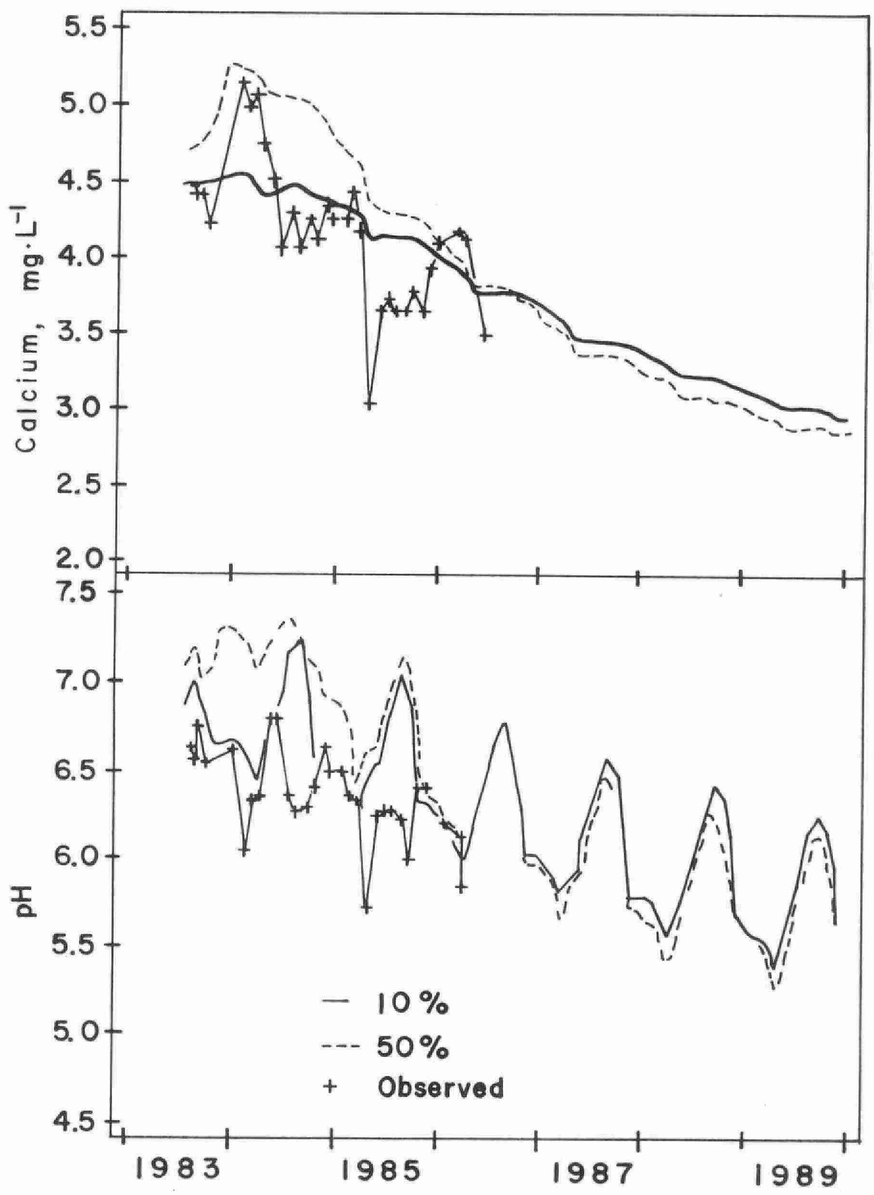


FIGURE 4: Predicted and observed reacidification of Bowland Lake. Observed pH and calcium concentrations are compared to the predictions of the Sverdrup model using the assumption that settled calcium covered 10% and 50% of the lake bottom.



was less. Approximately 25% of the added alkalinity was lost to reacidification in Trout Lake during the 18 months following treatment and, as with Bowland Lake, spring-melt depressions were more severe than the Swedish model had predicted (Fig. 5).

Spring-melt Chemistry

Nearshore water quality during spring-melt is important to the survival of lake trout eggs, sac fry and other biota inhabiting the littoral zone. Cold (less than 4°C), less dense meltwater entering the lake was confined to a surface layer less than 1 m deep directly under the ice. This surface layer spread over the surface of the lake but was more pronounced nearshore where close to a metre of ice forced meltwater into a narrow zone between the bottom of the ice and the surface of the substrate. The meltwater layer was more acidic than ambient lake water and tended to contain higher concentrations of aluminum and lower calcium and conductivity (Fig. 6, 7 and 8), although there were occasional events when very dilute acidic meltwater contained little aluminum.

Annual variation in chemistry was considerable, as was variation between sites, particularly for aluminum in meltwater. The size of the sub-watershed at each site correlated with meltwater total aluminum. The largest watershed corresponded with the highest aluminum levels in runoff, although not necessarily with the lowest pH.

Meltwater did not mix readily with neutralized lake water so that nearshore pulses of low pH, high aluminum, surface meltwater continued despite whole-lake neutralization. However, lake trout fry in Bowland Lake exposed in cages to nearshore water during spring-melt survived at five of six sites (Fig. 9) since cages were placed in water deeper than 1 m. At the sixth site mortality rates reached 100%. Neutralization did not protect the fish at this site and may have raised the pH to a level at which aluminum becomes toxic to fry. This situation also occurred at one site on Trout Lake where a large watershed fed a high concentration of both hydrogen ions and aluminum to the nearshore site.

FIGURE 5: Predicted and observed reacidification of Trout Lake. Observed pH and calcium concentrations are compared to the predictions of the Sverdrup model using the assumption that settled calcite covered 10% of the lake bottom.

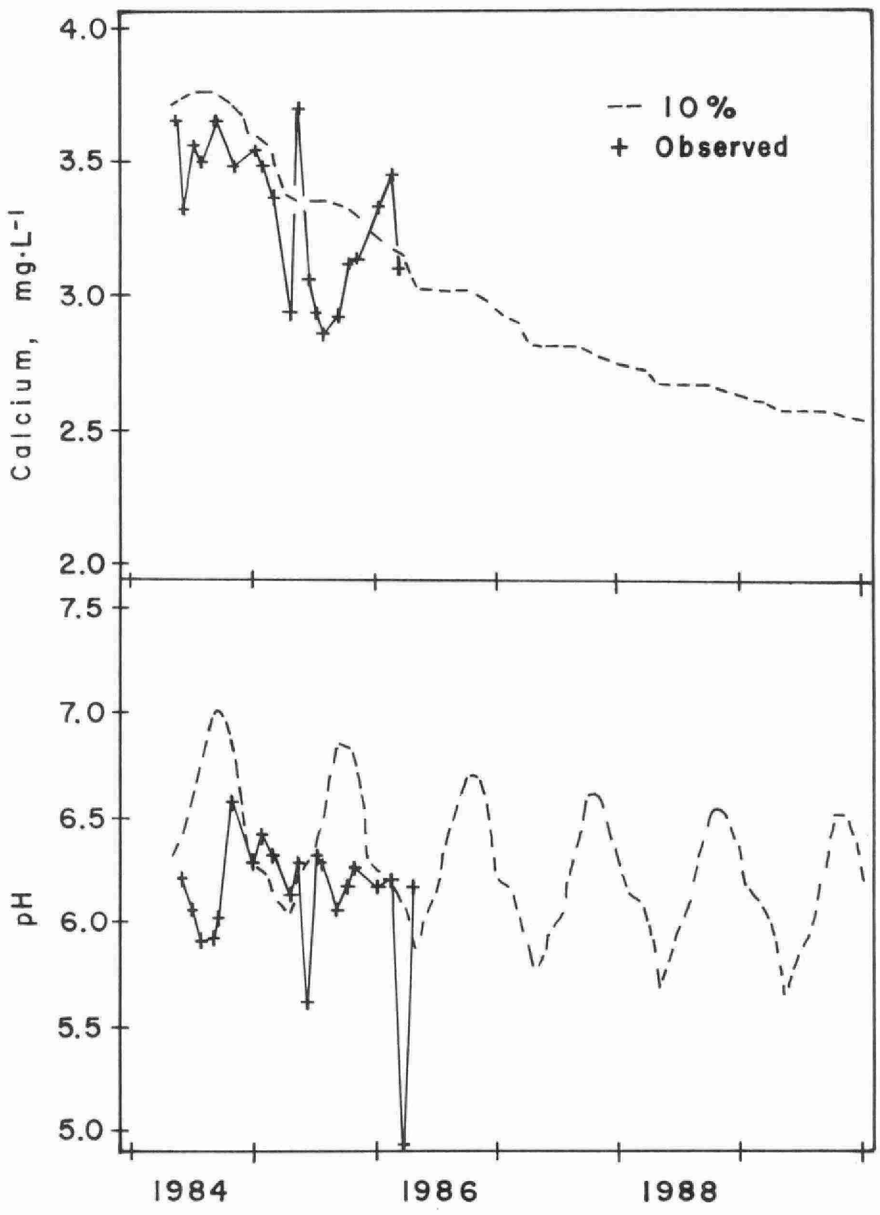


FIGURE 6: Daily pH, alkalinity (Alk), total aluminum (Al) and conductivity (cond) at the surface at a nearshore site (Site 5A), 0 m from shore, in Bowland Lake during spring melt in 1984. The midlake 1 m mean concentrations are also shown for reference.

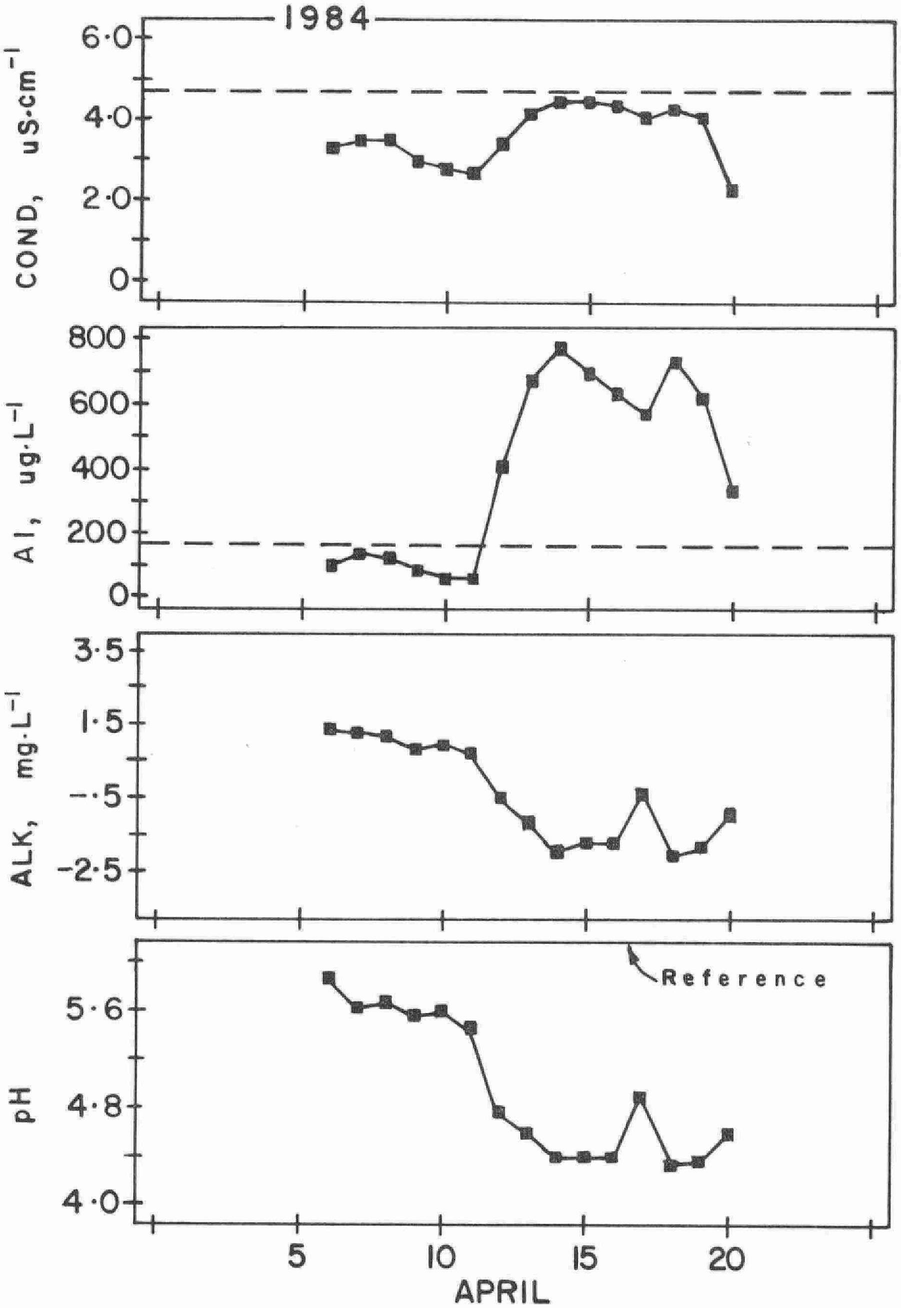


FIGURE 7: Daily calcium (Ca), total aluminum (Al) and pH at the surface at nearshore site, 0 m from shore, in Bowland Lake during spring melt in 1985. The midlake 1 m mean concentrations are also shown for reference.

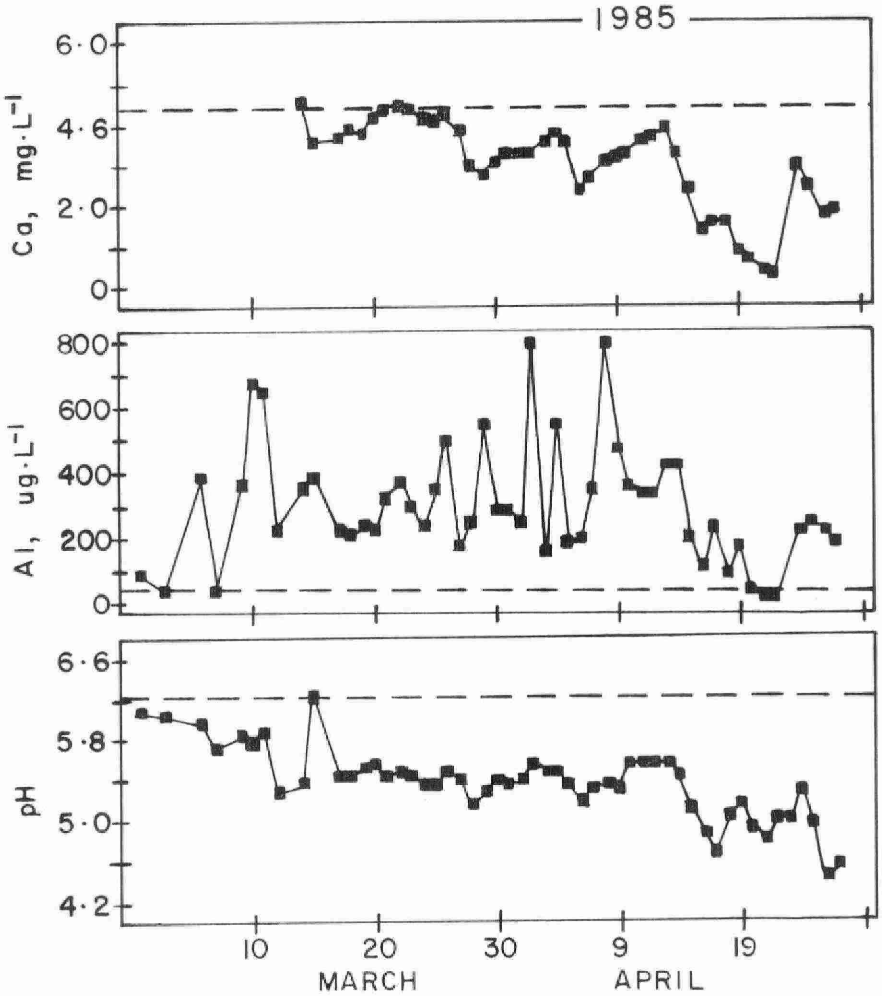


FIGURE 8: Daily calcium (Ca), total aluminum (Al) and pH at the surface of a nearshore site, 0 m from shore, in Trout Lake during spring melt in 1985. Midlake 1 m mean concentrations are also shown for reference.

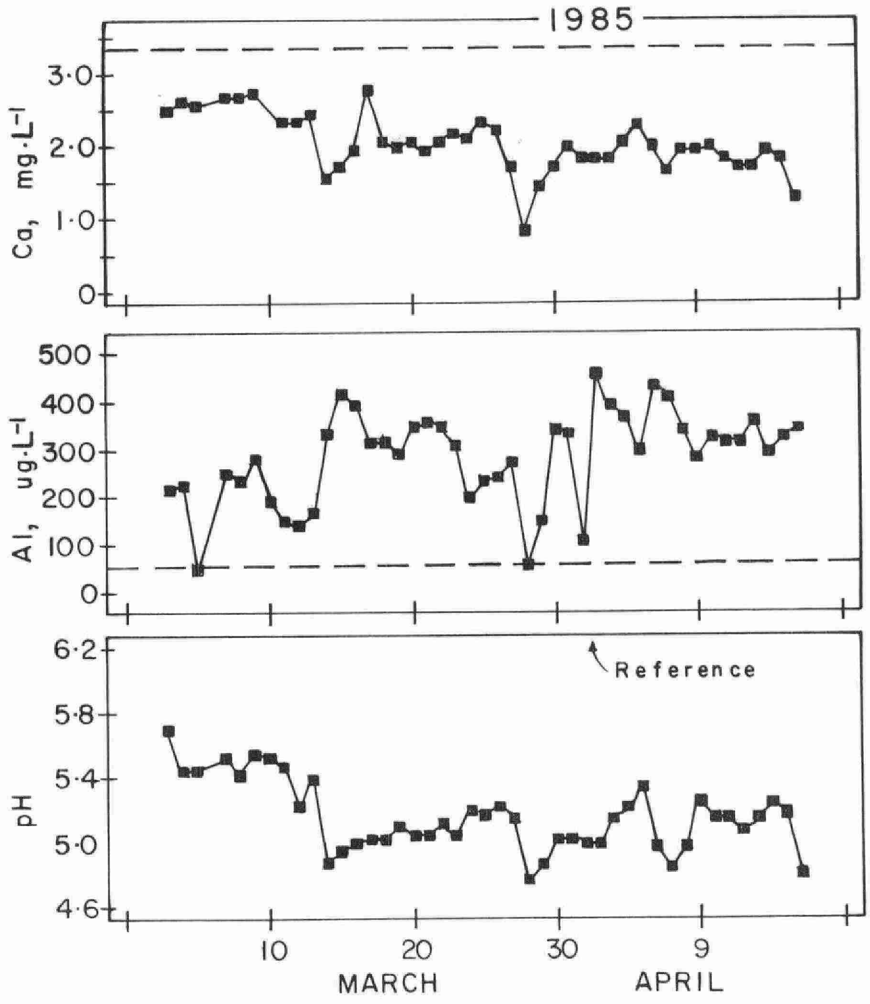
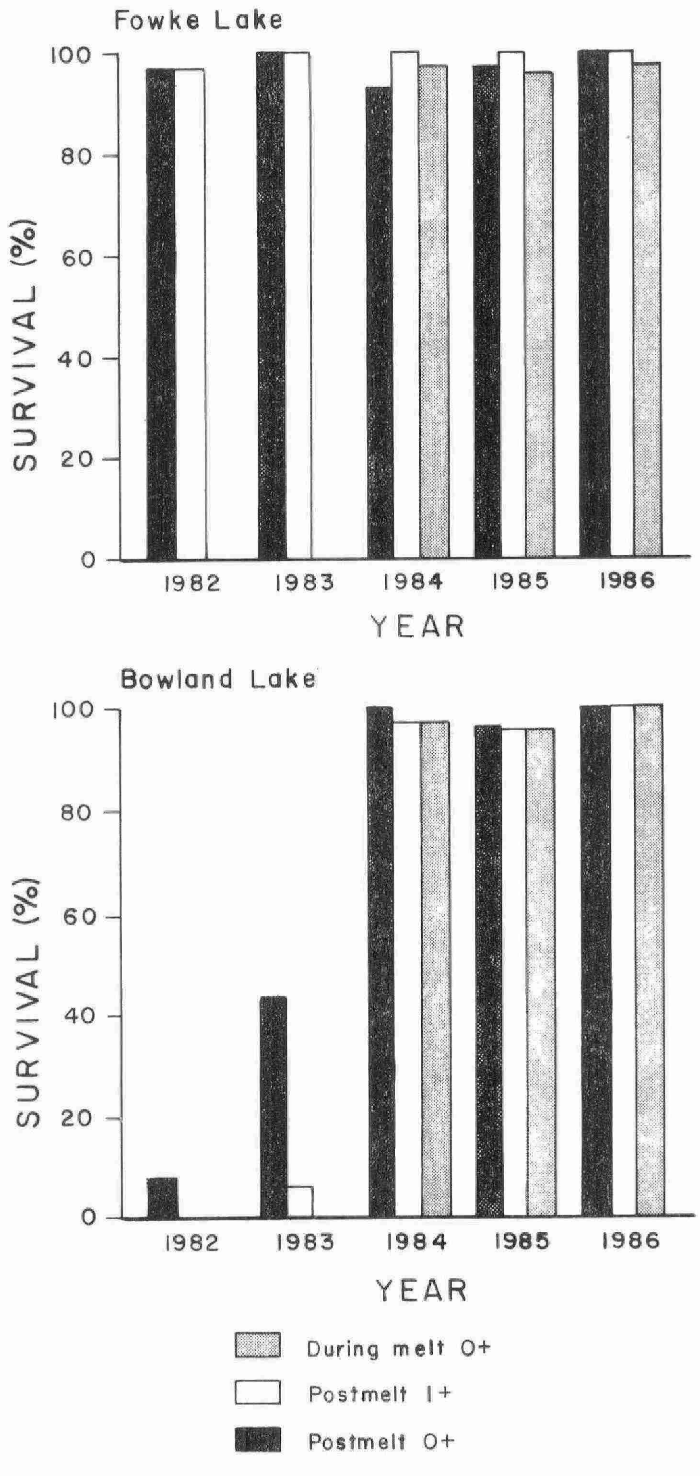


FIGURE 9: The percent of lake trout which survived exposures to Bowland Lake and to the reference lake, Fowke Lake, during spring in 1982 to 1986. Bowland Lake was neutralized in August 1983.



Water sampled at surface, bottom and interstitially a few metres offshore showed that only rarely was the surface plume of acidic meltwater entrained into the bottom or interstitial water (Fig. 10) suggesting that only at shallow, nearshore sites is runoff likely to reach lake trout eggs buried in the shoals.

Biological Responses

Benthic Algae and Macrophytes

A benthic algal community typical of acidic lakes was present in Bowland Lake before neutralization. In 1984, the year after neutralization, these acidophilic algae became rare. From 1985 to 1986, algal abundance returned to pre-neutralization levels although the species composition in 1986 was typical of a community undergoing acidification stress in contrast to the community of acidophilic species which was seen before neutralization. The aquatic macrophyte community was not affected by lake neutralization.

Phytoplankton and Zooplankton

After neutralization of Bowland Lake the phytoplankton community shifted from *Rhabdoderma*, a blue green algae, to a community dominated by several other species more typical of non-acidified systems.

The rotifer *Keratella taurocephala* that commonly dominates rotifer communities of acidic lakes in North America was dominant in Bowland Lake before treatment. After neutralization dominance shifted to rotifer species more characteristic of non-acidic lakes such as *Keratella cochlearis* and *Polyarthra sp*. The abundance of *K. taurocephala* also declined in Trout Lake after neutralization.

Crustacean zooplankton biomass in Bowland Lake (Fig. 11) decreased after neutralization coincident with increases in fish and phantom midge (*Chaoborus punctipennis*) populations, suggesting a predation effect. The biomass of ciliates and rotifers (Fig. 11) increased after

FIGURE 10: Daily inorganic aluminum (inorganic Al), pH, alkalinity and calcium from a nearshore site on Trout Lake in 1984 at the surface, on the lake bottom and from the interstitial gravel water (buried).

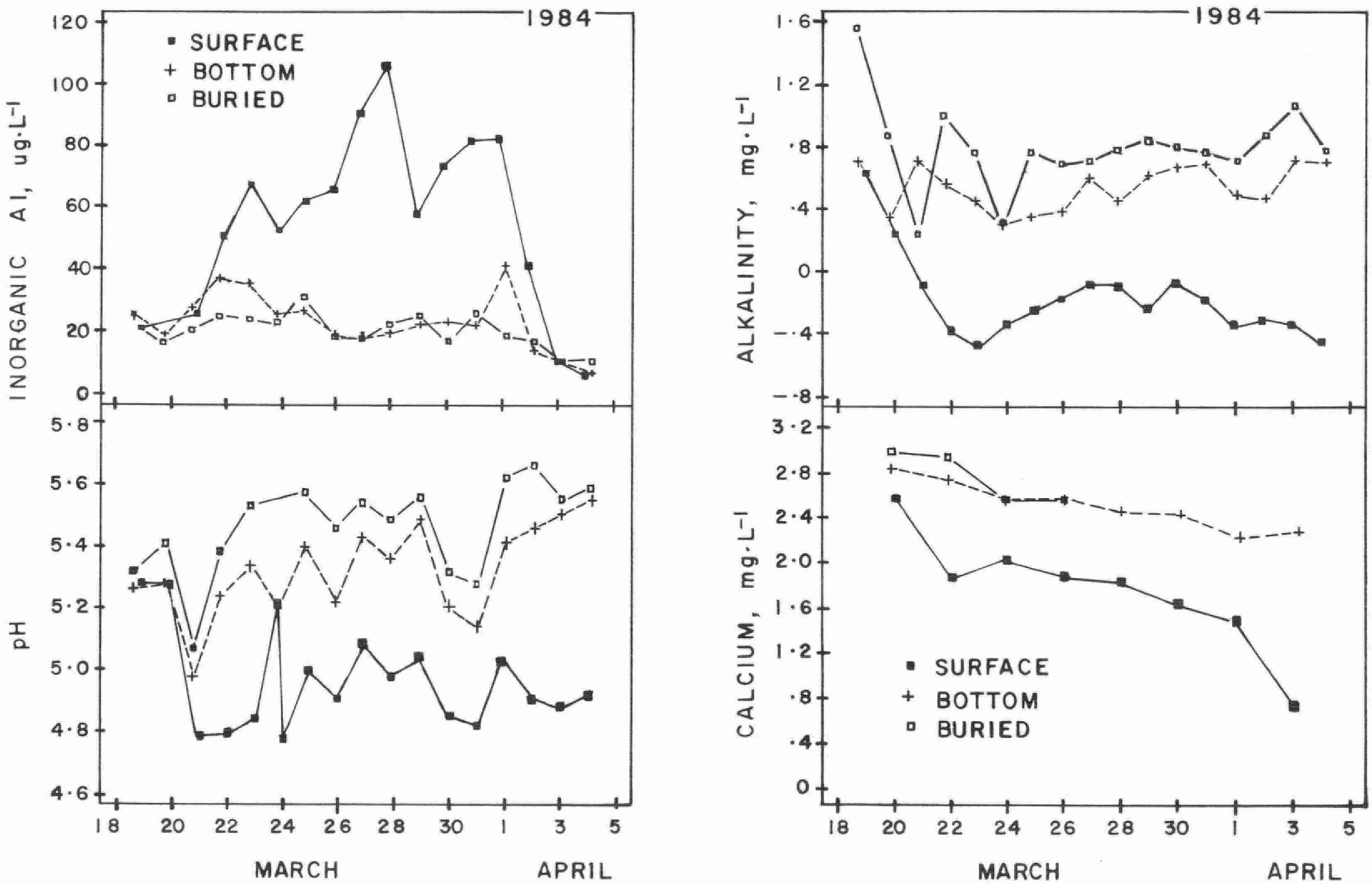
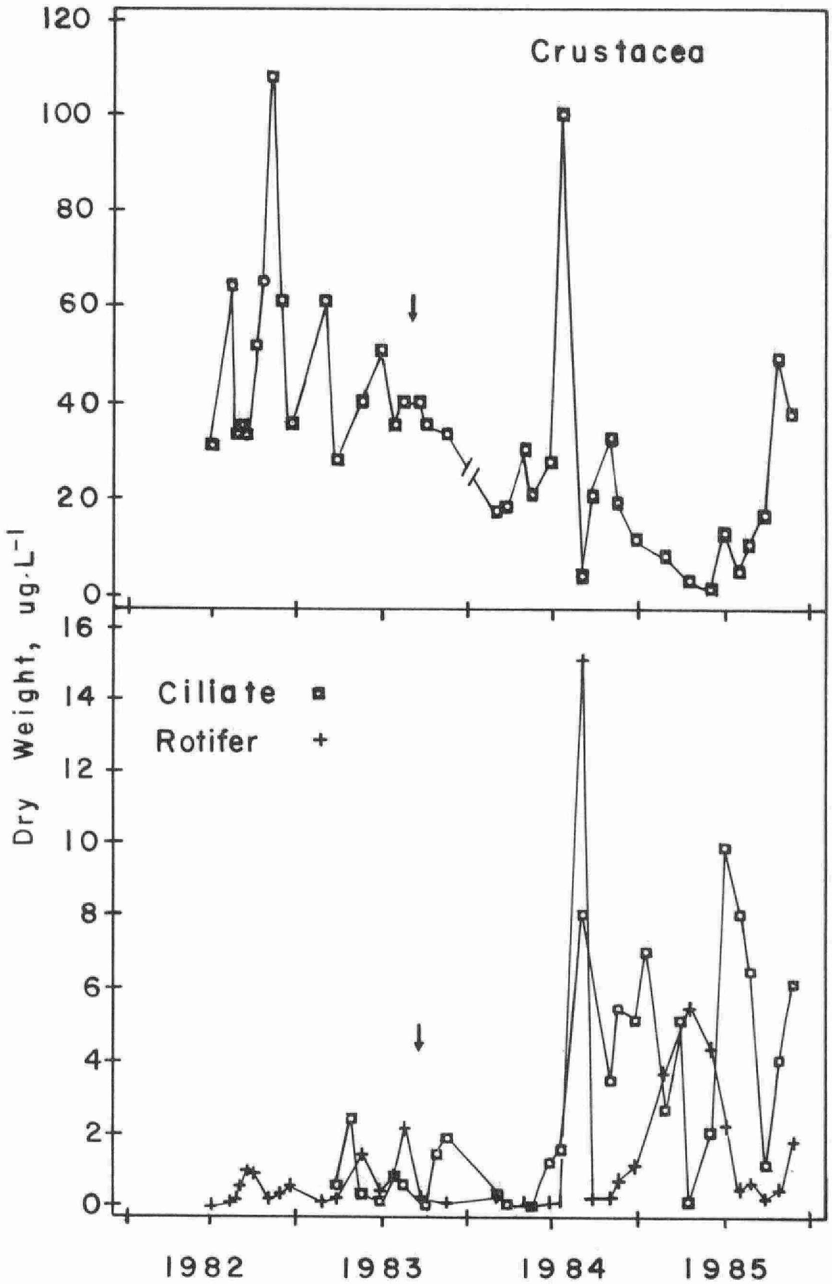


FIGURE 11: Biomass of planktonic crustaceans, rotifers and ciliates in Bowland Lake from 1982 to 1985. The arrow indicates the neutralization of Bowland Lake in 1983.



neutralization, apparently in response to reduced competition from crustacean zooplankton. There was no apparent increase in zooplankton community richness after neutralization, probably because of insufficient recolonization time. Based on preliminary examination of the data, no major changes in the zooplankton and phytoplankton communities of Trout Lake were apparent.

Benthic Invertebrates

Surveys of benthic invertebrates in Bowland Lake showed some changes in taxonomic composition that usually reflect improved water quality; however, many common acid sensitive species were still absent two years after neutralization. General decreases in benthic invertebrate biomass and reduced average organism size after neutralization were observed, probably caused by intensive predation by fish.

No benthic surveys were performed on Trout Lake; however, a significant post-neutralization increase in the abundance of opossum shrimp (*Mysis relicta*), an important invertebrate predator and forage species for fish, was evident from limited survey data.

Fish Community

Before Bowland Lake was neutralized, bioassays of lake trout eggs on the surface of shoals 2-10 m from shore (1-2 m of water), showed almost total mortality. Survival rates improved after neutralization with eggs in Bowland Lake surviving at least as well as controls in Fowke Lake (Fig. 12). An improvement in survival rates after neutralization occurred in Trout Lake; however, a similar although less pronounced improvement in egg survival in unlimed Miskokway Lake bioassays suggested that higher survival on these two lakes may have been partly due to factors other than neutralization, such as the warmer temperature in October in Miskokway Lake and handling differences associated with loading the eggs into the incubators.

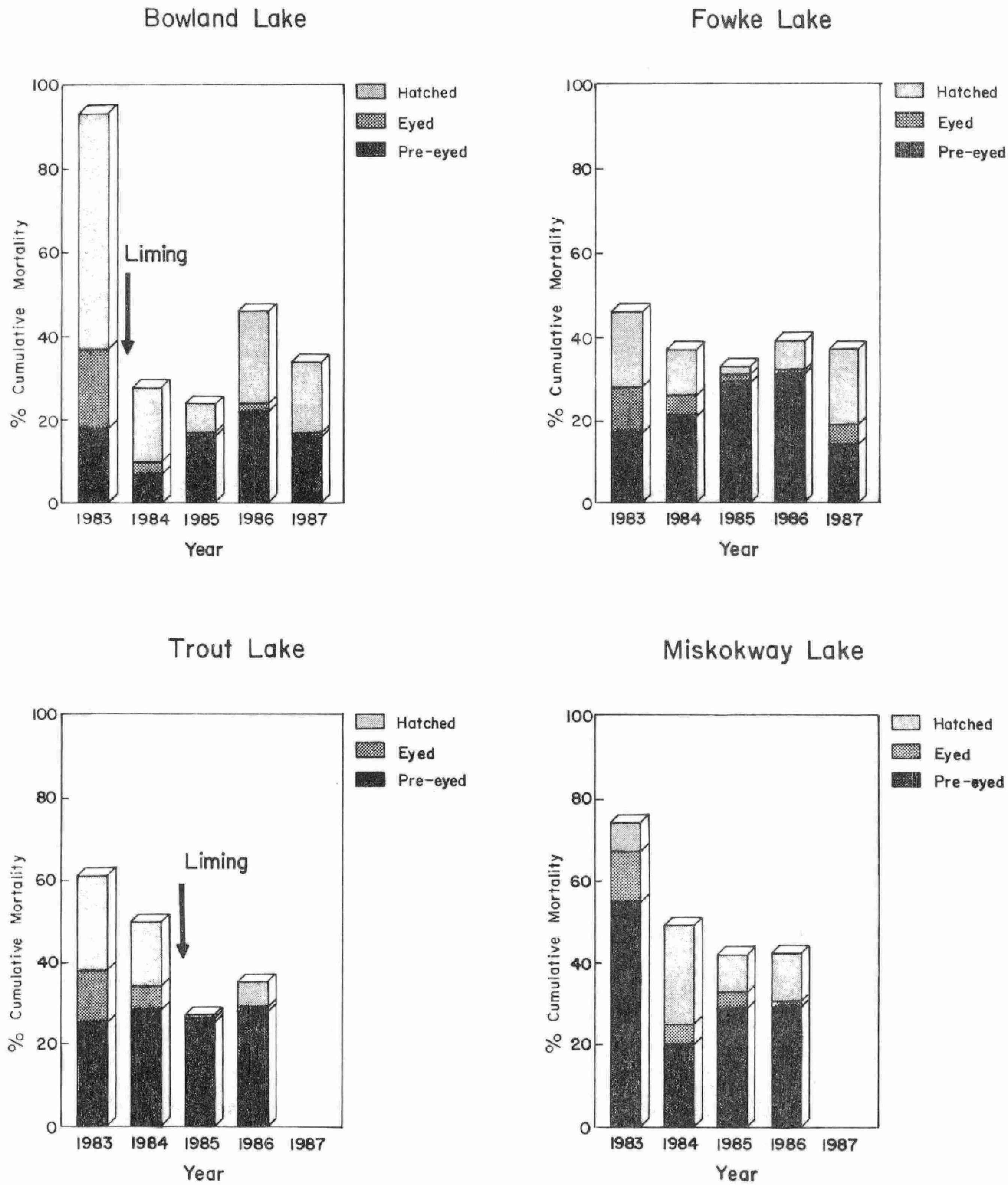


FIGURE 12: Cumulative mortality at various stages of development of overwintering lake trout eggs in Bowland and Trout Lakes before and after neutralization and the corresponding reference lakes, Miskokway and Fowke Lakes, from the fall of 1982 (spring 1983) to the spring of 1987. The graphs show the developmental phase of the embryos when they died.

These results suggest that whole-lake neutralization improves survival of the early developmental stages of lake trout at sites which are deeper than 1 m. Natural spawning sites chosen by stocked lake trout in Bowland Lake and by native lake trout in Trout Lake, were all shallower than 1 m. As seen in the nearshore chemistry surveys, shoals which were shallower or closer to shore might not have been protected by lake neutralization. The results of the bioassay experiments may, therefore, overestimate the benefits of whole-lake neutralization for protecting early life stages of lake trout during spring-melt because the experiments were in deeper water and farther from shore.

The neutralization of Bowland Lake in 1983 was followed by the reintroduction of lake trout. The first successful spawning of lake trout was confirmed in 1985/86. Although emerging lake trout fry were collected from the spawning shoals in 1986, recruitment to older year-classes has not yet been confirmed.

Adult lake trout transferred to Bowland Lake exhibited little, if any growth. Hatchery-reared lake trout stocked into Bowland Lake in 1983 and 1984 grew well initially (Fig. 13) but their growth stopped and condition factors dropped by the fall of 1985 (Fig. 14). Two hundred additional two year old hatchery lake trout were stocked in 1985 and may have affected the growth of the established lake trout population because of intra-specific competition for a limited food resource. Growth and condition factors increased again in the fall of 1986, perhaps because the lake trout began to feed on the abundant perch supply. Stomach analyses, however, were not available to confirm this theory.

The perch population size initially increased after neutralization; however, the increase was consistent with favourable weather conditions in the summer of 1983, when perch in many other lakes produced larger year classes and thus may not have been related to neutralization. Growth rates of perch improved after neutralization but then declined, and by 1986 were similar to those seen before the treatment. These growth rates suggest that competition was also affecting perch.

FIGURE 13: Growth rates of 3 distinct cohorts of lake trout, stocked in Bowland Lake after its neutralization.

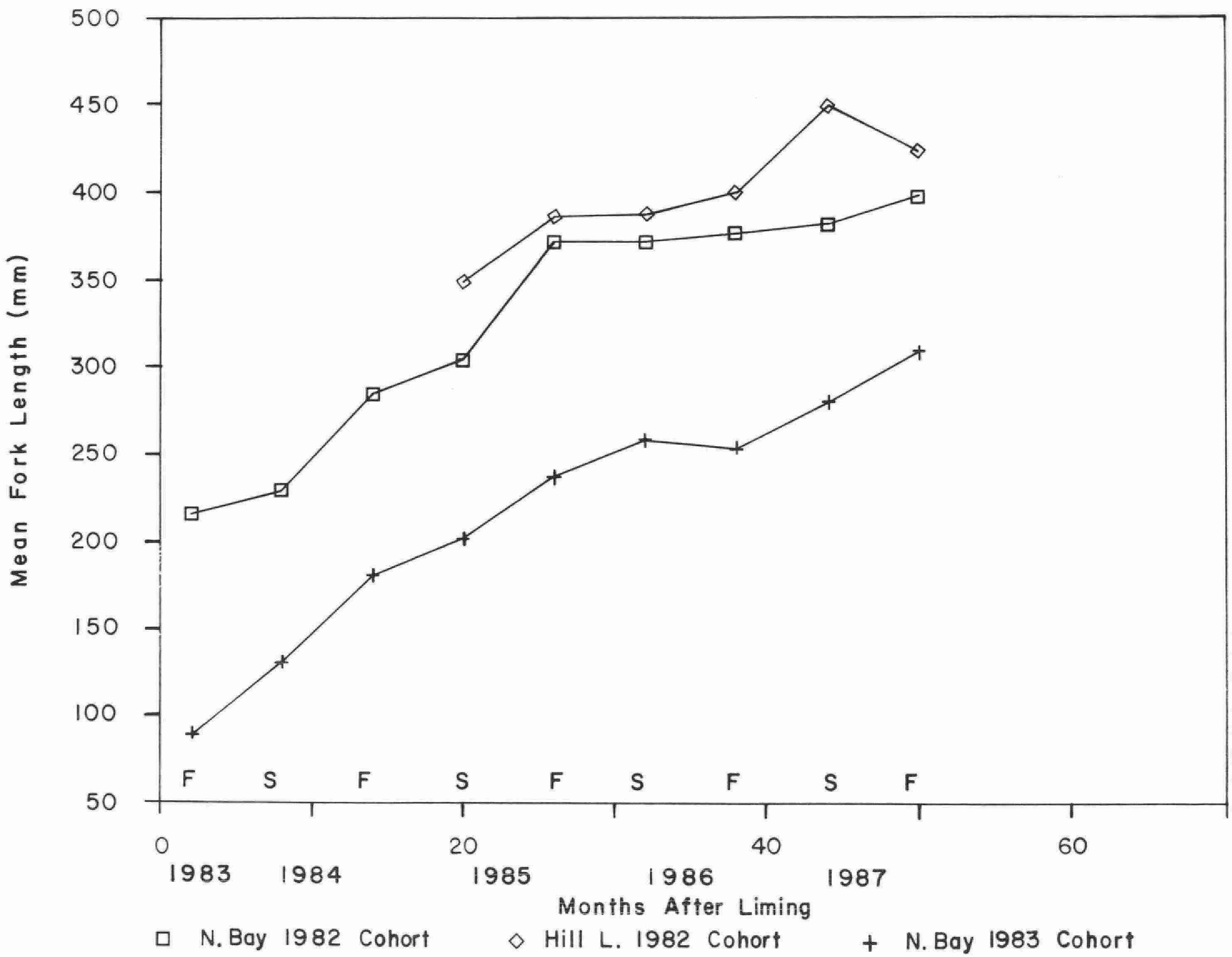
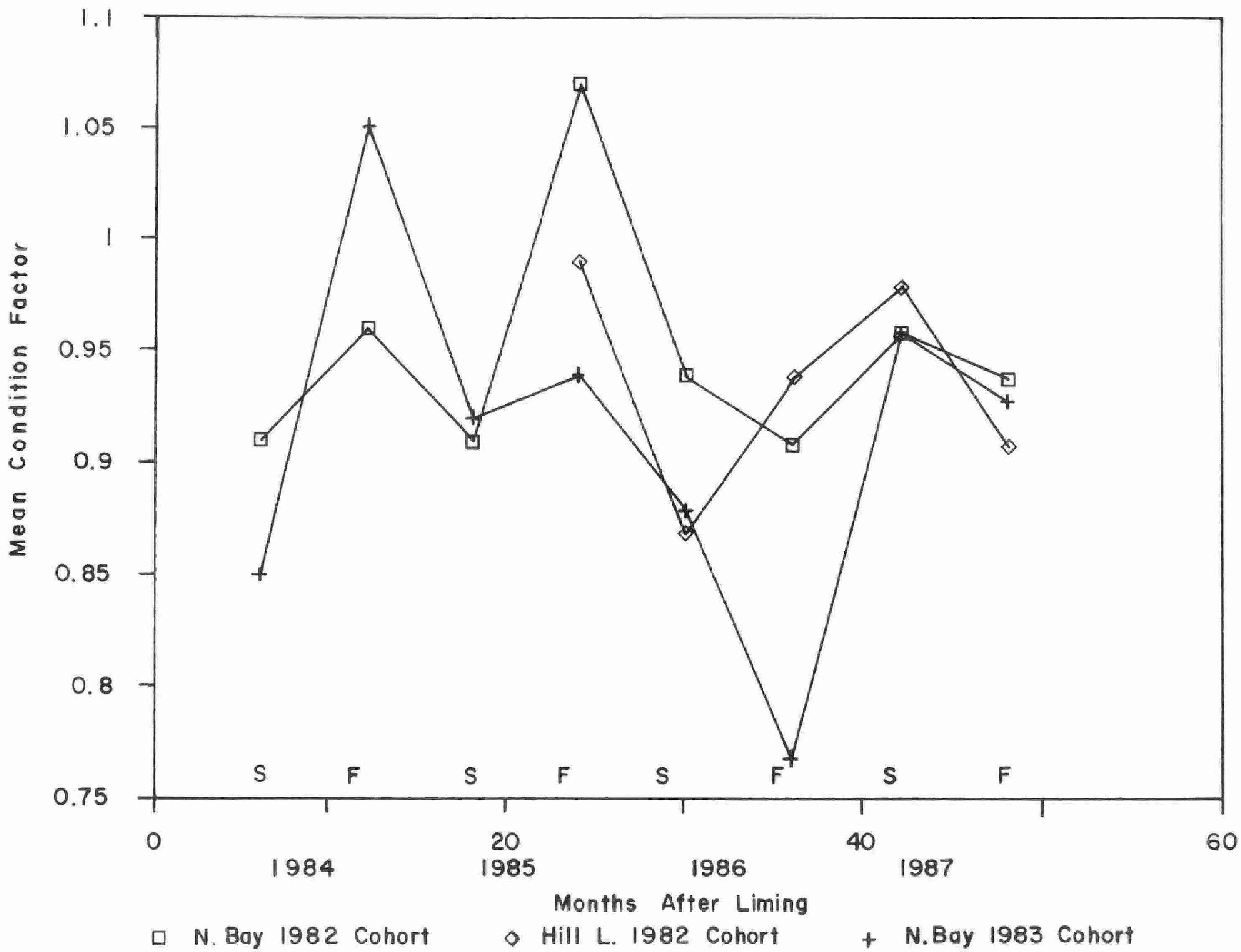


FIGURE 14: Condition factors of 3 distinct cohorts of lake trout, stocked in Bowland Lake after its neutralization.



Trout Lake supported a diversity of fish species before neutralization. Only minor changes in abundance or community composition were apparent among the three major species investigated in the two years after treatment. All these changes could be attributed to normal annual variation. It is premature to speculate regarding the response of lake trout recruitment to neutralization in Trout Lake, since cohorts produced after neutralization will not enter the fishery until 1988 at the earliest. Any changes seen in the lake trout population in the future must also be considered in light of the closure of the winter lake trout fishing season implemented concurrently with neutralization.

In both Bowland and Trout lakes, the mercury concentration in fish increased for one year following neutralization, but decreased to preliming values the next year. The change in body concentration of mercury is likely unrelated to neutralization; however, this trend to higher mercury body burdens after neutralization was detected in Scandinavian studies. Bioaccumulation of mercury following neutralization could endanger the goals of creating/protecting sport fish populations; however, in Bowland and Trout lakes, the highest mercury concentrations in fish were still below the recommended consumption guideline of 0.5 ug/g.

Shoal Liming

Water quality within the neutralized shoals on Laundrie Lake improved. The response in terms of survival of lake trout eggs buried in the shoal was not conclusive due to small sample sizes and relatively low rates of mortality at the control sites. Further work is continuing in a more acidic lake during the next phase of the study to provide a better test of the technique.

The lake trout in Miskokway Lake showed neither avoidance of, nor attraction to the natural spawning shoal that was treated with limestone, suggesting no negative behavioural responses to the calcite treatment.

UNCERTANTIES

Although lake neutralization improves water quality, the technique provides only a temporary solution. Continuing acidic precipitation and runoff will cause the neutralized lake to return to its previous acidified state. Additional application of limestone to Bowland and Trout lakes is not planned now. The effects of reacidification on the lakes are unknown.

There are uncertainties associated with productivity and biomass changes in lakes that have been neutralized. More research is needed to determine if the forage base in acidified lakes is suitable to sustain an introduced fishery. Better understanding of fish growth rates is also needed to distinguish between natural variability and changes induced by indirect or direct effects of the treatment. It is also still uncertain if invertebrate populations will return to original preacidified levels and remain healthy.

Further trials are necessary to test the neutralization of lake trout spawning shoals on a management scale. Recent experiments were not conclusive due to small sample sizes and because of relatively low rates of mortality at even the control sites.

Overall, whole lake neutralization is a promising technique for lake rehabilitation; however, more monitoring is needed to address unanswered questions about long term effects.

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